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Jong, Joost J.M. de; Vries, Arjen C. de; Klaassen, Wim

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INFLUENCE OF OBSTACLES ON THE AERODYNAMIC ROUGHNESS OF THE NETHERLANDS

JOOST J. M. DE JONG, ARJEN C. DE VRIES and WIM KLAASEN
Department of Physical Geography, University of Groningen, Kerklaan 30, 9751 NN, Haren, The Netherlands

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Abstract. The aim of this study was to analyse the influence of large- and small-scale obstacles (orography, tree lines, and dikes) on the effective aerodynamic roughness of the Netherlands, a relatively flat, small-scale landscape. The roughness averaging approach was based on drag coefficients. The effective roughness was locally dominated by small-scale obstacles such as tree lines and dikes. Even at a regional scale (40,000 km^2), the small-scale obstacle drag was of the same order of magnitude as the shear stress due to landuse. The neglect of those obstacles on a regional scale would result in approximately 10% overestimated averaged windspeed at 10 m above the surface. It was concluded that small-scale obstacles need to be taken into account to calculate the aerodynamic roughness of flat landscapes. Orography was of minor importance in this lowland country.

Keywords: Aerodynamic roughness, Flat landscape, Obstacles, Orography, Roughness length, Tree lines.

1. Introduction

One of the important processes at the interface of the earth's surface and the atmosphere is the exchange of momentum. It directly influences the air flow and indirectly the exchange of heat and gases. Momentum transfer needs to be quantified for purposes such as weather prediction (Mason, 1988), estimation of wind turbine power supply (WMO, 1981), rainfall evaporation modelling (Mahfouf and Jacquemin, 1989), air pollution deposition modelling (Erisman, 1992) and climate change modelling (Sud et al., 1988).

For momentum transfer modelling over homogeneous surfaces, the land surface can be characterised by the aerodynamic roughness length (z_0). This roughness length is defined by the logarithmic wind profile, and is valid in the lower part of a neutrally stratified boundary layer. Over heterogeneous land surfaces, the boundary layer is disturbed by variations in the aerodynamic roughness of the surface. In such cases an effective aerodynamic roughness length z_0^{eff} accounting for the heterogeneity of the earth's surface is used. Heterogeneity due to landuse variations is basically two-dimensional.

In addition, the effective aerodynamic roughness is increased by small obstacles such as isolated trees, hedges, tree lines, houses and dikes (Wieringa, 1993). Klaassen and Claussen (1995) showed theoretically that by neglecting these small-

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scale obstacles most existing aggregation schemes for grid-averaged fluxes in large-scale models underestimate the influence of landscape variability. Measurements above a flat landscape consisting of fields of 200 $\times$ 200 m surrounded by hedges of 4 m in Great Britain indicate that the form drag generated by the field boundaries causes nearly an order of magnitude increase in the effective roughness length (Hopwood, 1996). Similar results were found in a Chinese agricultural landscape with fields of 150 $\times$ 150 m surrounded by tree lines of 12-m height (Wang and Klaassen, 1995).

The above mentioned studies were carried out in small-scale landscapes leaving the question whether the effect of small-scale heterogeneity is still important at a larger scale. A preliminary study of Venema (1995), who wrapped tree lines over a regularly spaced grid and used the one-dimensional flux aggregation model of Claussen and Klaassen (1992), indicated a regional effective roughness length increment for the Netherlands of one order of magnitude. This result stands as an upper boundary for the influence of small obstacles, because irregular spacing results in mutual shading and thus a smaller drag.

It is generally accepted that large-scale orographic features can increase or even dominate the effective roughness length (e.g., Kustas and Brutsaert, 1986; Taylor et al., 1989; Wood and Mason, 1993). Although orography locally influences the effective aerodynamic roughness in the Netherlands (Wieringa, 1986), orographic features cover only about 3.5% of the Dutch surface (LKN, 1997), and the question remains whether orography also influences the effective roughness at a larger scale in such a landscape.

Therefore, the aim of this study is to determine the influence of small-scale obstacles and orography on the aerodynamic roughness of relatively flat, small-scale landscapes. To analyse this significance, the effective roughness length of the Netherlands, a densely populated coastal lowland, is calculated on a 1 $\times$ 1 km grid with special emphasis on the influence of small-scale obstacles and orography. These roughness lengths are aggregated for all of the country (40,000 km^2) to derive the regional effective aerodynamic roughness. These calculations are executed assuming neutral stability. To asses the influence of small-scale obstacles and orography on the applications mentioned in this introduction, the near-surface wind speed is calculated.

2. Method

Above heterogeneous surfaces, the effective roughness length z_0^{eff} is a suitable parameter to help quantify the momentum flux τ between the atmosphere and the earth's surface. The momentum flux is commonly parameterised as a function of two atmospheric variables, the density of air ρ and the wind speed u, and a variable representing the frictional effects of the earth's surface, the drag coefficient C_d:

$$\tau = C_d \rho u^2. \tag{1}$$

For neutrally stratified near-surface situations, the drag coefficient is a function of the height z and the roughness length z_0:

$$C_d = \left(\frac{0.4}{\ln(z/z_0)}\right)^2. \tag{2}$$

Due to the linearity of C_d in formula (1), as compared to the logarithmic scaling of z_0, it is common to add local drag coefficients to obtain the grid-cell specific drag. The effective roughness length z_0^{eff} can be calculated from this drag using Equation (2). As drag coefficients are height dependent, first a suitable height must be determined. At small heights, the wind is adjusted to the surface patch directly beneath it. At a higher level, the wind changes from local equilibrium with the horizontal surface to independence of horizontal position (Mason, 1988). This level is defined as the blending height and is a suitable height for adding drag coefficients. In the past, the blending height has been considered to depend on the landscape scale (Mason, 1988; Claussen, 1991) or the vegetation height (Wieringa, 1993). Thus, the blending height is a grid cell resolution independent parameter related to characteristics of the earth's surface. Following Van Dop (1983), Wieringa (1986) and Erisman (1990), the empirical height of 10 m above the surface is used for addition of drag coefficients.

As mentioned in the introduction, two types of surface features contribute to the effective roughness length: landuse and obstacles. Obstacles are present at various scales. Henceforth, large-scale obstacles will be referred to as orography and small ones, such as tree lines and dikes, as small-scale obstacles (SSO). In case both orography and small-scale obstacles are present, the small-scale obstacles can be considered as part of the surface drag (Taylor et al., 1989). Therefore, first the influence of small-scale obstacles and landuse will be quantified, and next the influence of orography.

A wake with less shear stress develops at the downwind side of an obstacle resulting in a smaller surface frictional drag of the intervening surface. If the obstacle interspacing is sufficiently large, more than 15 times the obstacle height, then obstacle drag and surface friction drag are approximately additive (Marshall, 1971), so:

$$C_d = C_d^{\mathrm{landuse}} + C_d^{\mathrm{SSO}}. \tag{3}$$

The landuse drag is calculated using an area-weighted averaged drag coefficient (Van Dop, 1983):

$$C_d^{\mathrm{landuse}} = \sum_i f_i C_{d,i}^{\mathrm{landuse}}, \tag{4}$$

where f_i is the subgrid land fraction and $C_{d,i}$ the drag coefficient of each type i of landuse. The latter are computed with Equation (2) from the roughness lengths of homogeneous surfaces. The small-scale obstacle drag coefficients are aggregated using:

$$C_d^{\mathrm{SSO}} = \sum_i C_{d,i}^{\mathrm{SSO}}. \tag{5}$$

The individual obstacle drags $C_{d,i}^{\mathrm{SSO}}$ are calculated with Equation (2) from the roughness lengths of obstacles obtained by the classic empirical formula of Lettau (1969):

$$z_{0,i}^{\mathrm{SSO}} = c_{s,i} \frac{h_i^2}{s_i}, \tag{6}$$

where

$$s_i = \frac{A}{0.5 l_i}.$$

In this equation: $c_{s,i}$ is a form constant, h_i the obstacle height, s_i the spacing between the obstacles, and i refers to the type of small-scale obstacle. The spacing is obtained from the subgrid length l_i of the obstacle and the grid cell area A. The factor 0.5 is introduced into this formula as it is assumed that half the obstacles are positioned perpendicular to the wind direction.

Linear averaging of drag coefficients (Equations (3)–(6)) accounts for some interaction due to the transition of a surface-adjusted flow to an areally-averaged flow at the blending height (Klaassen and Claussen, 1995). In the case of roughly vegetated, undulating hills the interaction between form drag and surface friction occurs at a larger scale and has to be included more explicitly (Mason, 1985). Therefore, the aerodynamic roughness by orography is determined by (Taylor et al., 1989):

$$\ln\left(\frac{z_0^{\mathrm{eff}}}{z_0}\right) = A\left(\frac{2\pi a}{\lambda}\right)^2 \ln\left(\frac{\lambda}{z_0}\right), \tag{7}$$

where

$$a = 0.5H$$

$$\lambda = \frac{2H}{\tan\alpha}.$$

This formula is based on model calculations of flow over sinusoidal topography with a wavelength λ, an amplitude a, and a surface roughness length z_0. The variable A is a tuning constant. The wavelength and the amplitude are calculated from the slope angle α and the elevation transition H of the dominant relief. The surface roughness length is computed from the surface drag C_d with Equation (2). Taylor et al. (1989) tuned this equation with two-dimensional models and found $A = 3.5$. The current approach is three-dimensional, and therefore it is similar to small-scale obstacles, assuming that the orographic contribution of each hill side to the effective roughness length occurs only half the time, whence a value of 1.75 is used for A. Equation (7) is only valid if the flow does not separate from the hill's surface. Kaimal and Finnigan (1994) estimated separation to occur at downwind slopes steeper than 10°, as most Dutch hills have slope angles of 3 to 8° separation will hardly occur and Equation (7) may be used.

The influence of the various obstacles via the effective roughness length on the near surface windspeed is estimated following Wieringa (1986) by transforming the geostrophic wind down into the boundary layer with standard Rossby-number similarity theory for a neutral atmosphere. A fixed effective geostrophic wind of 11 m s^{-1} is assumed at the top of the boundary layer. This value approximates the annually averaged geostrophic wind over the Netherlands (Wieringa, 1986). Because standard meteorological measurements are taken at 10 m above the surface, the near-surface windspeed is calculated at this height.

3. Data

Maps with a resolution of 1×1 km originating from the digital Landscape Ecological Atlas of the Netherlands (LKN, 1997) were used as model input. The study area, the Netherlands, is 40,100 km^2 large. The atlas is based on several sources, among others 1:25,000 topographic maps and geomorphologic maps. The atlas contains the subgrid fractional landuse in hectare per grid cell for the 13 landuse classes listed in Table I. Roughness lengths published by Wieringa (1993) and Erisman (1992) were assigned to these landuse classes. The landuse classes of the atlas were not in all cases appropriate for this assignation. The major shortcoming of the atlas classification was that dunes and sand are one landuse class, while sand in dunes is mostly covered by beach grass. By assigning the roughness length of sand (0.0005 m) to the dunes, we underestimate their effective roughness length. This underestimation is expected to be small as rough dune vegetation such as forest and bushes are taken into account. In the Dutch landscapes, the main small-scale obstacles are buildings, tree lines, dikes and forest edges. Due to the relatively large length of dikes and tree lines, it was assumed that only these obstacles contribute to the small-scale obstacle drag. The atlas contains the subgrid length of tree lines and dikes in km km^{-2}. In the Netherlands, the total length of tree lines is 12,352 km and the length of dikes is 7,459 km. The individual small-scale obstacles heights were not known. Therefore, these obstacle heights were approximated by the averaged heights: tree lines 13 m (Knol, 1992), and dikes 3 m (pers. comm. Body of Surveyors of the Dikes 'Boarn en Klif'). Lettau (1969) estimated for trees and meteorological towers a form constant, c_s of 0.5, which we applied for tree lines.

TABLE I

Landuse types and roughness lengths.

Landuse	Roughness length (m)
Coniferous and mixed forest	1.2
Deciduous forest	1.2
Grass	0.019
Agriculture (crops)	0.11
Tree nursery, orchard, poplar plantation	0.8
Marshland	0.04
Heath, bog	0.04
Sand, dune	0.0005
Tidal flat, saltmarsh	0.0005
Fen	0.08
Water	0.0002
Urban green	0.8
Urban	0.95

Dikes are smoother, and so a form constant of dikes was chosen as 0.2, a value also used for hills (Smith and Carson, 1977). The dominant relief was given by the atlas in 13 classes based on local height difference and slope angle. The major hills have an elevation of $\pm$ 60 m and a slope angle smaller than 8°. In the south, higher hills are found and along the coast some low, steep dunes. An impression of the spatial distribution of landuse is shown in Figure 1.

4. Results

The effective roughness length was calculated with and without small-scale obstacles and orography on a 1×1 km grid, and by aggregating the drag coefficients to one effective roughness length for all of the Netherlands. The compiled effective roughness length map is presented in Figure 2. The regional effective roughness lengths, and the resulting estimated influence on the horizontal windspeed at 10 m are listed in Table II. The spatial influence of the small-scale obstacles is shown in Figure 3. The roughness length computed without tree lines and dikes was locally up to 95% and regionally 38% smaller than the roughness length computed with small-scale obstacles. Tree lines and dikes had a large influence in landscapes dominated by grass and agriculture and a small influence in urban and forested areas. The 38% increased regional effective roughness length results in a 10% decreased windspeed at 10 m. Assuming a logarithmic wind profile, this deviation will be larger near the surface. The orographic influence can be seen in Figure 4. By

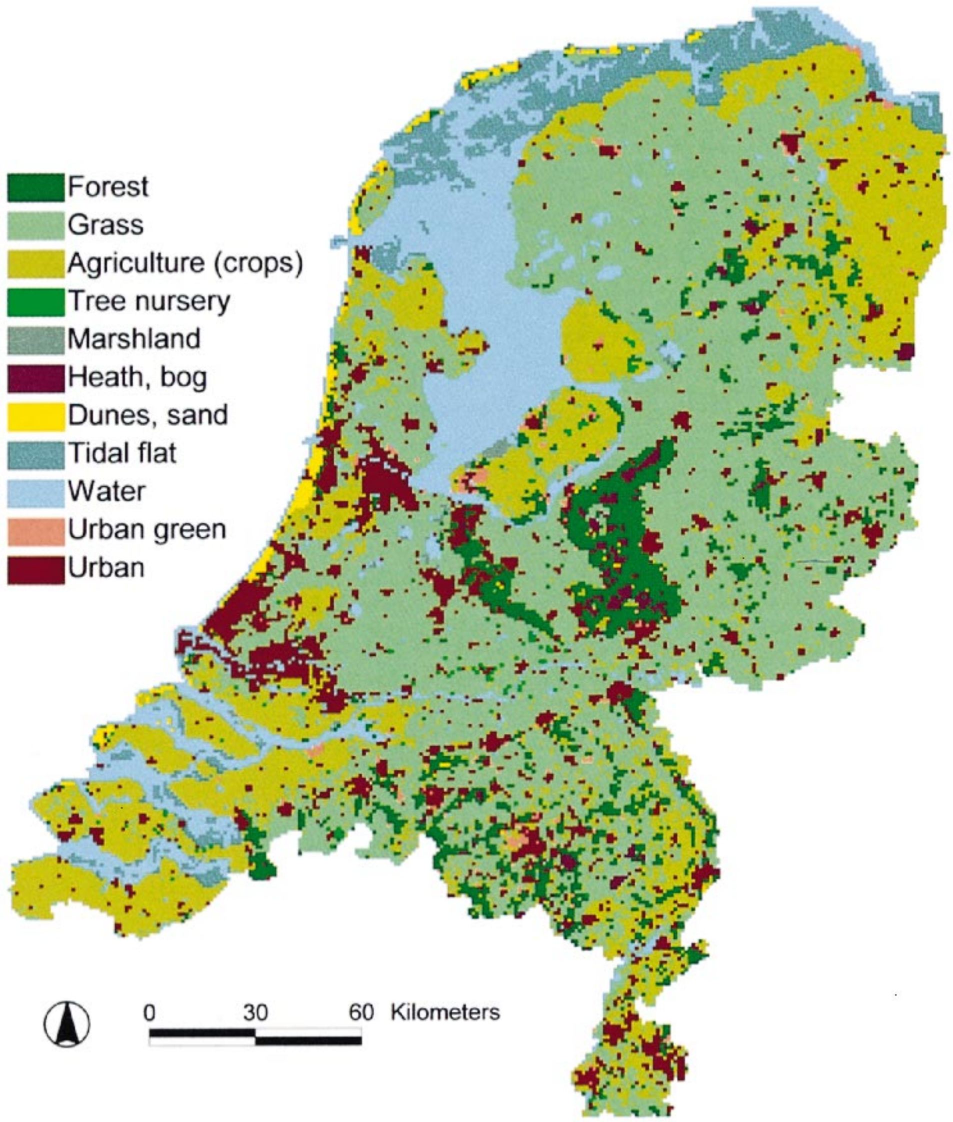

Figure 1. Dominant landuse in the Netherlands (source LKN, 1997). Note: this study uses the subgrid fractional landuse.

neglecting orography, the effective roughness length was locally underestimated by up to 67%. The regional effective roughness without orography was 3.6% smaller than the effective roughness with orography. The local influence of the orography was particularly large along the coast in the dunes, and in the south where the highest hills are found. The orography had only a minor influence on the windspeed at 10 m.

TABLE II

Aggregated effective roughness length of the Netherlands, and the resulting windspeed at 10 m.

Factors included	z_0^{eff}, m	$u(10)$, m s^{-1}
Landuse	0.204	4.64
Landuse, orography	0.214	4.60
Landuse, small-scale obstacles	0.322	4.26
Landuse, orography, small scale obstacles	0.334	4.23

5. Discussion

Meteorological field stations are generally located at large distances from rough elements such as houses, forests and tree lines. Therefore, the roughness lengths derived from data collected at these field stations are not representative of a heterogeneous grid cell and so we could, regrettably, not validate the compiled roughness map on these measurements. Instead, the reliability of the compiled map is assessed by comparing it with the roughness length map published by Wieringa (1986). This map was compiled by explicitly accounting for landuse and orography, and implicitly accounting for small-scale obstacles. The latter by assuming that roads and canals are tree lined (this is expressed through a z_0 of 0.24 m), if the area covered by roads and canals is at least 10% of a 5 $\times$ 5 km pixel. The advantage of the present approach is that the impact of small-scale obstacles is determined more objectively. The patterns and order of magnitude of our roughness length map compiled without small-scale obstacles agrees well with Wieringa's map. However, our roughness length map compiled with small-scale obstacles shows an enhanced roughness in flat areas with a high density of tree lines. This agreement with Wieringa's map leaves the question whether the estimated influence of small-scale obstacles is reasonable.

The most striking result is the large influence of the small-scale obstacles. For heterogeneous landuse, the subgrid obstacle spacing is assumed to be constant within the grid cell, and the wake behind an obstacle is neglected. The calculated minimum spacing is 17 times the averaged tree line height, so in the current approach an obstacle does not lie within the wake of the previous obstacle. In a real landscape, some of the obstacles are situated in the wake of an upstream obstacle, and therefore the assumption of a constant subgrid spacing may result in an overestimation. The drag of the wake area is small compared to the total drag of the landscape. Therefore, summation of obstacle drag and landuse drag is a reasonable approximation, resulting in only a restricted overestimation of the surface roughness. On the other hand, we use the averaged tree-line height and dike

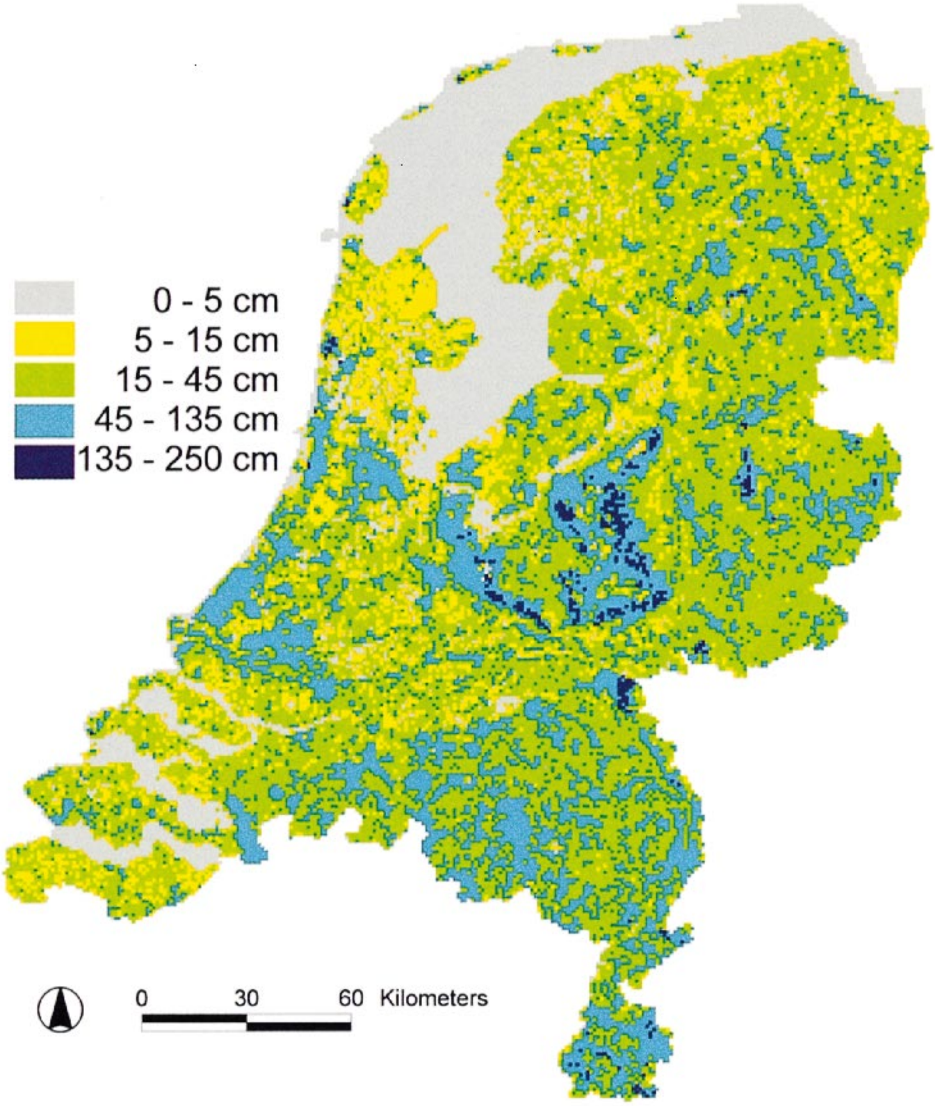

Figure 2. Effective roughness length in the Netherlands calculated by accounting for landuse, orography and small-scale obstacles.

height. Because the obstacle drag is a quadratic function of the obstacle height, this assumption can result in an underestimation of the effective roughness length. Furthermore, the overestimation of obstacle drag will be compensated by the neglect of obstacles such as isolated farms, trees and forest edges. The drag of the intervening surface is determined by the roughness lengths of homogeneous surfaces (see Table I). These values are averages over a range of measured roughness lengths. The local

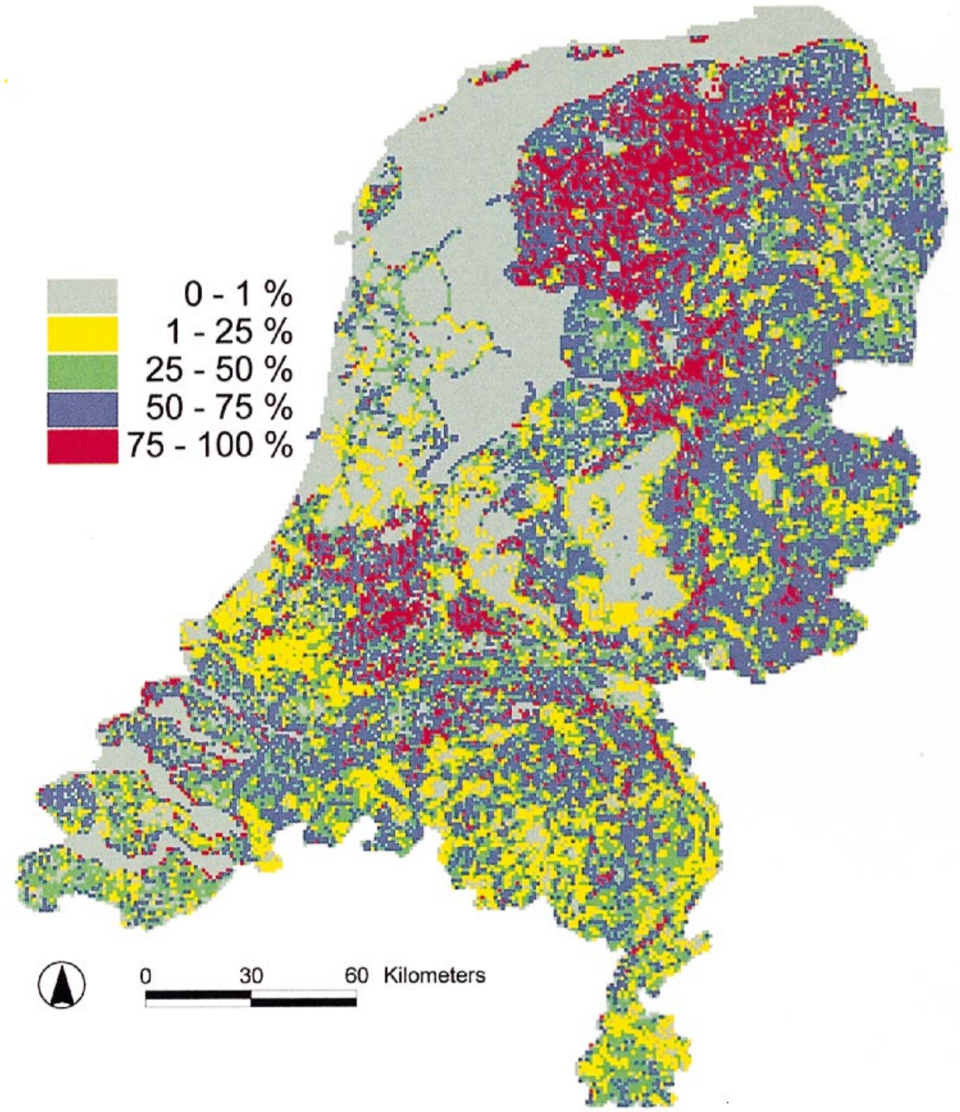

Figure 3. Percentage underestimation of the effective roughness length if tree lines and dikes are neglected.

deviation of this average may be large, for instance when dunes are covered by shrubs. On a regional scale this variation in local roughness is expected to average out. The resulting effective roughness length including small-scale obstacles is locally up to one order of magnitude larger than the effective roughness length without small-scale obstacles. This is in agreement with measurements (Wang and Klaassen, 1995; Hopwood, 1996) in areas with a high density of small-scale ob-

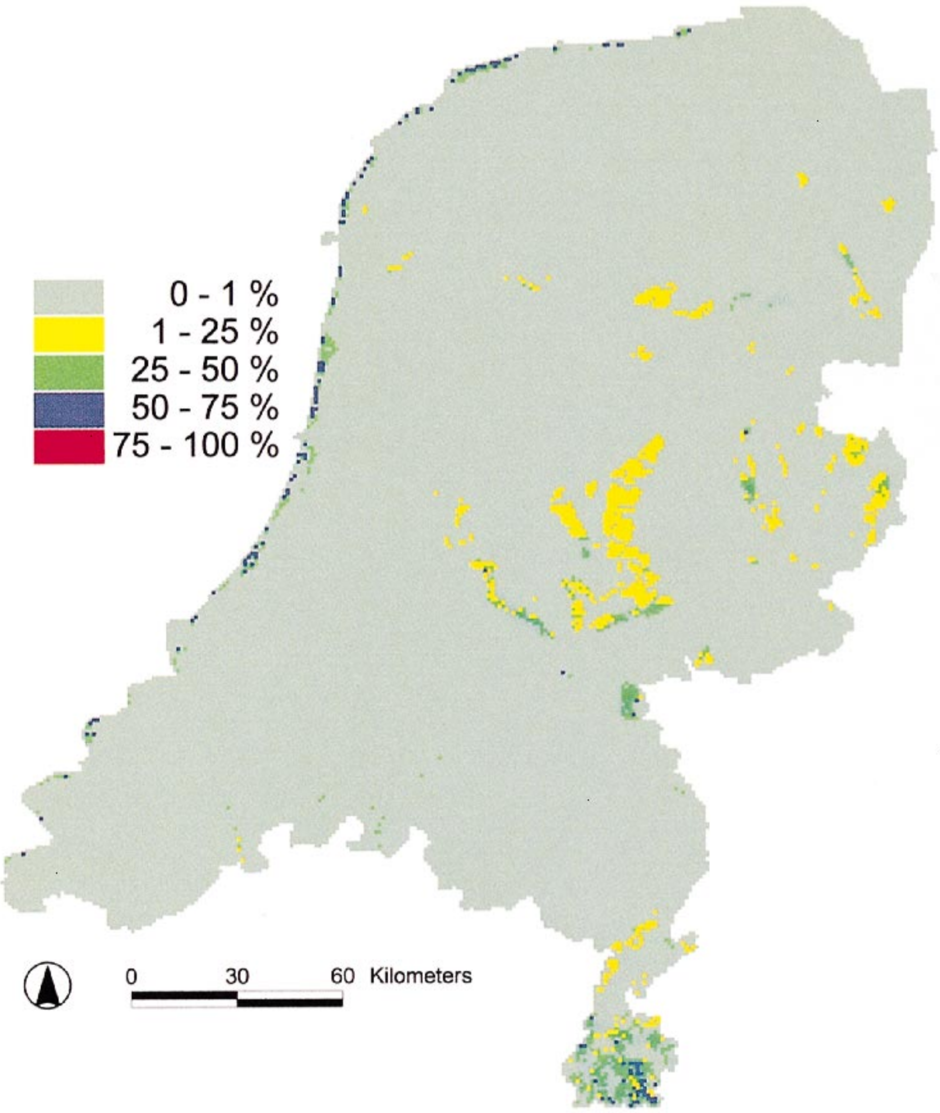

Figure 4. Percentage underestimation of the effective roughness length if orography is neglected.

stacles. It indicates that the calculated influence of small-scale obstacles is indeed realistic.

The second result is the limited influence of orography. The influence of orography is relatively high in the dunes, which are considered as low hills. As stated before, the dunes surface roughness is underestimated by the neglect of low vegetation. For low hills, a smooth surface causes a larger relative increment than a rough surface. So, the relative influence of orography in dunes is overestimated. The influence of the orography is calculated with a semi-empirical model (Taylor et al., 1989) which is based on a two-dimensional sinusoidal topography. It neglects three-dimensional effects. Compared to a detailed three-dimensional model, the way we used Taylor's model may result in a slight overestimation of the effective roughness length (Wood and Mason, 1993). So, the influence of orography is limited in the Netherlands.

The approach is based on a fixed blending height of 10 m. Another proposed blending height is 60 m (Wieringa, 1986; Agterberg and Wieringa, 1989). For the small-scale landscape of the Netherlands, the difference in surface roughness due to landuse calculated with a blending height of 10 m and a blending height of 60 m is less than 20% for 90% of the pixels (Agterberg and Wieringa, 1989). As demonstrated by Bottema et al. (1998), the sensitivity of the results to the choice of the blending height decreases by including obstacle drag. The latter study showed that by including obstacle drag the effective roughness length of a partly forested area calculated with a blending height varying between 7 m and 125 m deviates by only a few percent. Therefore, the exact level of the blending height is of minor significance for this study.

6. Conclusion and Recommendations

Small-scale obstacles such as tree lines and dikes can be the dominant momentum-absorbing elements at the landscape scale (1–10 km) in the Netherlands, a densely populated lowland area. At larger scale (40,000 km^2), their influence on the effective aerodynamic roughness is of the same order of magnitude as the influence of landuse. Regionally, accounting for tree lines and dikes results in approximately 10% decreased windspeed at 10 m height. The influence of orography is locally as important as the surface roughness, but on average orography can be ignored in this flat country.

Neglecting obstacles and especially small-scale obstacles would result in an underestimation of the effective roughness length of lowlands. It is therefore recommended to incorporate small-scale obstacles into the roughness length maps of flat areas such as river deltas. The influence of obstacles depends on the dimensions of all obstacles (obstacle height, width, spacing). This information can be established with airborne laser altimeter measurements (De Vries et al., 1998).

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